Modelling Indoor Air Quality

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ADMS-Urban & ADMS-Roads User Group Meeting

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Contents

- Introduction and background
- Motivation for model development
- Modelling indoor air quality - general
- Indoor air quality model
- Model evaluation
- Conclusions and next steps

Introduction

- **Motivation for model development**
  - Current interest in indoor air quality
  - People spend a lot of time indoors (on average ~ 90%)
  - Indoor air quality measurements providing data for model evaluation
  - Indoor air quality model can link to ADMS outdoor concentration distributions
- **Issues**
  - Indoor emissions may not be well specified
  - Personal behaviour strongly influences indoor air quality
  - Improving energy efficiency can lead to improvements in air quality if combustion sources (e.g. gas boilers & cookers) removed; deterioration if ventilation reduced (e.g. new builds)
  - Important indoor pollutants include NO_2 ,PM, CO, CO_2, VOCs and biological aerosols due to damp/mould

Background

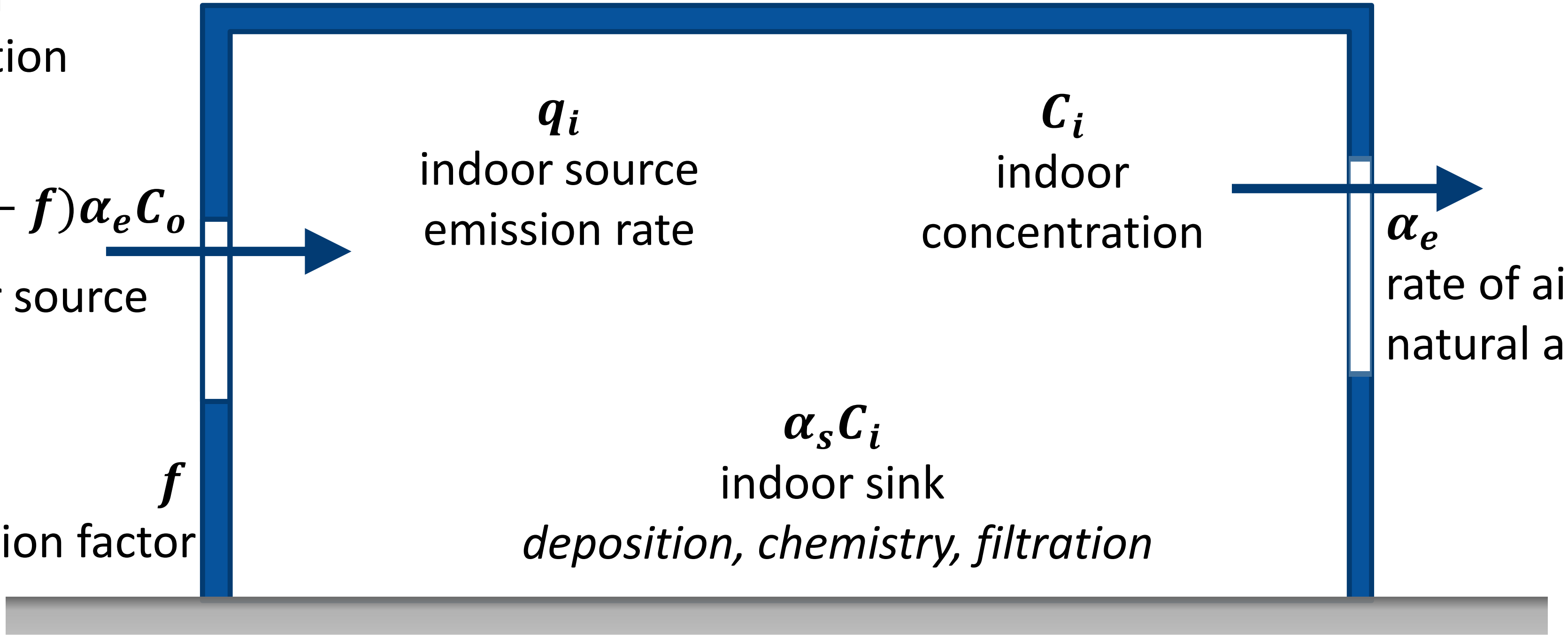
- CERC have conducted numerous (natural) ventilation studies including a study of Glyndebourne Opera House
- Contributed to Defra’s Air Quality Expert Group’s (AQEG) ‘Indoor Air Quality’ report (2022)
- Part of the National Institute for Health Research-funded ‘Indoor HABItability during the Transition to Net Zero Housing’ (INHABIT) Hub, working with the University of Edinburgh

Modelling indoor air quality – General

- **Indoor emission source strengths have high uncertainty, however dispersion constrained by buildings**
  - If time scale for mixing in rooms/building (τ_m) small compared to timescales for changes in indoor sources, ventilation rate and outdoor concentrations, details of (complex) turbulent mixing may not be important
  - For room with sides length 5 m and turbulent velocity ~ 0.05 m/s, τ_m ~ 100 s
  - Well-mixed approximation for modelling good starting point; contrast outdoor dispersion
  - Measured concentrations can be used to make some deductions about indoor source strengths, ventilation and sinks (e.g. deposition); contrast outdoor dispersion where inverse modelling is complex

Modelling indoor air quality

Key processes determining indoor air quality (ignoring room to room exchange)



Modelling indoor air quality

- **Factors affecting indoor concentration C_i :**
  - **Indoor sources:** q_i (emission rate)

    - Emission rate of $PM_{2.5}$ from gas cooker typically less than 1 µg/s

    - An emission rate of 1 µg/s well mixed into a room of 4×4×2.5 = 40 m^3 will result in concentration of 90 µg/m^3 after one hour, if no ventilation

    - Emission rate of NOx from gas cooker typically less than 10 µg/s

    - Typical CO_2 exhalation rate from a person is about 11.6 mg/s (1 kg/day). A person entering a 40 m^3 room will result in increase of CO_2 concentration of about 500 ppm after 1 hour, if no ventilation

Modelling indoor air quality

- **Factors affecting indoor concentration C_i:**
  - **Ventilation:** air exchange rate α_e

    Range from $\ll$ 1 to $\gg$ 1 air exchanges per hour; for example Bradford study 0.002-1.67 m^3/s

  - **Outdoor sources:** $q_o = (1 - f)\alpha_e C_o$ (ingress from outdoors, filtration factor f)
    Equivalent source strength based on external concentration of C_o=40 µg/m^3 and one air exchange per hour for our 40m^3 room is 0.44 µg/s

  - **Indoor sinks:** Chemical reactions & deposition ($\alpha_s C_i$)

    Typical deposition rate ~ 0.1 mm/s

Indoor air quality model

- Assumes conservation of mass and well mixed in single room:

$$V\frac{dC_i}{dt} = q_i + q_o - (\alpha_e + \alpha_s)C_i$$

Factors affecting indoor concentration $\boldsymbol{C_i}$:

$\boldsymbol{q_i}$: (emission rate) - Indoor sources

$\boldsymbol{q_o}$: Outdoor sources - (ingress from outdoors, with filtration factor f)

$\boldsymbol{\alpha_s}$: Sinks - Chemical reactions & deposition ($\alpha_s C_i$)

$\boldsymbol{\alpha_e}$: Ventilation **-** air exchange rate

Indoor air quality model

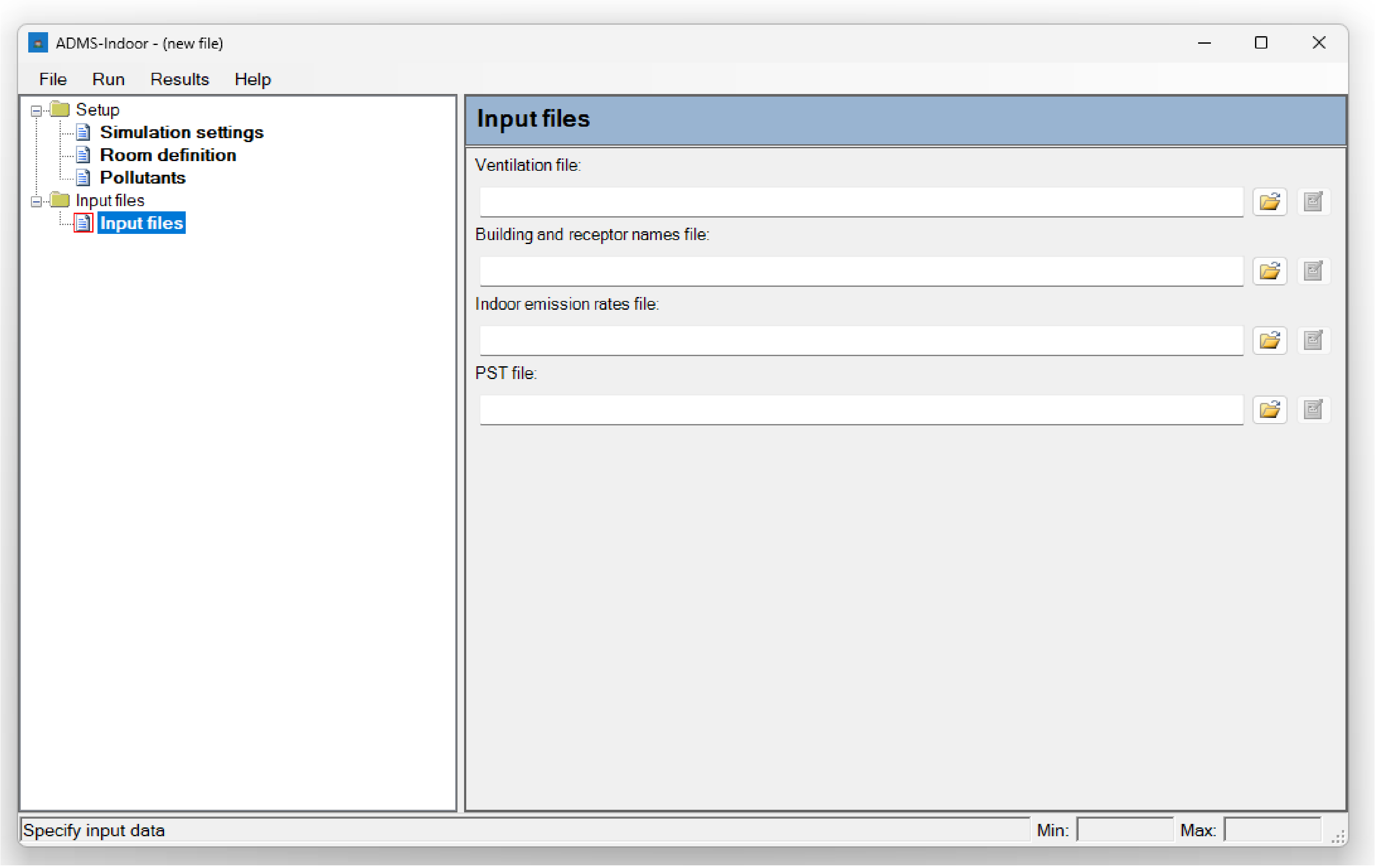
Analytic solutions of equation

- If source emission rates and rates of air exchange are constant in time then for indoor concentration $C_i = 0 \; at \; t = 0$ solution is:
  - $C_i = \frac{(q_i + q_o)}{(\alpha_e + \alpha_s)} \left\{ 1 - exp\left(- \frac{(\alpha_e + \alpha_s)}{V} t \right) \right\}$
- For steady state conditions solution is:
  - $C_i = \frac{(q_i + q_o)}{(\alpha_e + \alpha_s)}$
- If indoor source q_i is turned off at $t = 0$ and the concentration is already in equilibrium:
  - $C_i = \frac{q_i}{(\alpha_e + \alpha_s)} \exp\left(- \frac{(\alpha_e + \alpha_s)}{V} t \right) + \frac{q_o}{(\alpha_e + \alpha_s)}$

This shows how indoor concentrations return to equilibrium with outdoor concentrations, e.g. the fall in CO_2 concentrations after people leave a room

Indoor air quality model – implementation

- Simulation settings: time duration, timestep, plotting options
- Room definition: volume
- Pollutants: specify pollutants, associated deposition values
- Input files
  - Ventilation file
  - Building and receptor names file
  - Indoor emission rates file
  - Outdoor concentrations (ADMS .pst) file



Model evaluation

- Datasets of **indoor** and **outdoor air quality measurements** are available
- Other datasets required as input to modelling are often limited and harder to collate:
  - **Indoor emissions** are usually derived from activity data.
    - Activity data can be specific (e.g. from diaries) or assumed (e.g. daily behaviours)
    - Emissions factors per unit activity are in the literature, but can vary by orders of magnitude
  - **Air exchange rates** are often derived from the relationship between measured outdoor and indoor CO_2 concentrations during periods when the building is empty

Model evaluation: examples

Activity	Key pollutants	Dataset(s) considered to date
Cooking and movement	**$PM_{2.5}$**, *PM_{10}*	Data from a Bradford household study, shared by University of Cambridge*
Other household combustion, e.g. boilers	*NO_2*	*Not yet identified*
Classroom	**CO_2**	Data from the literature (published by *)
Smoking (plus cooking and movement)	**$PM_{2.5}$**, *PM_{10}*	Hybrid data assuming smoking activities in the Bradford household, compared to indoor air quality measurements from the literature

Items in italics not presented

* Dr Lia Chatzidiakou, Department of Chemistry, University of Cambridge

Household part of the 'Born in Bradford' cohort

Bradford: cooking and movement setup & assumptions

- $PM_{2.5}$ air quality measurements:
  - Indoor measurements from a living room of a house in Bradford
  - Outdoor concentrations from a measurement site (could be ADMS modelled data)
- Period considered: October 2023 – December 2024
- Activity considered: general movement + cooking at mealtimes
- Ventilation rate estimated by UoC from the reduction in CO_2 during uninhabited periods
  - Ventilation rate ranges from 0.002 - 1.7 m^3/s [$\ll$ 1 to $\gg$ 1 air exchanges per hour]
- Kitchen (55.8 m^3) and living room (46 m^3) volumes combined
- 4 – 7 residents
- No filtration. Deposition velocity = 0.19 mm/s

Bradford: $PM_{2.5}$ general activity data processing

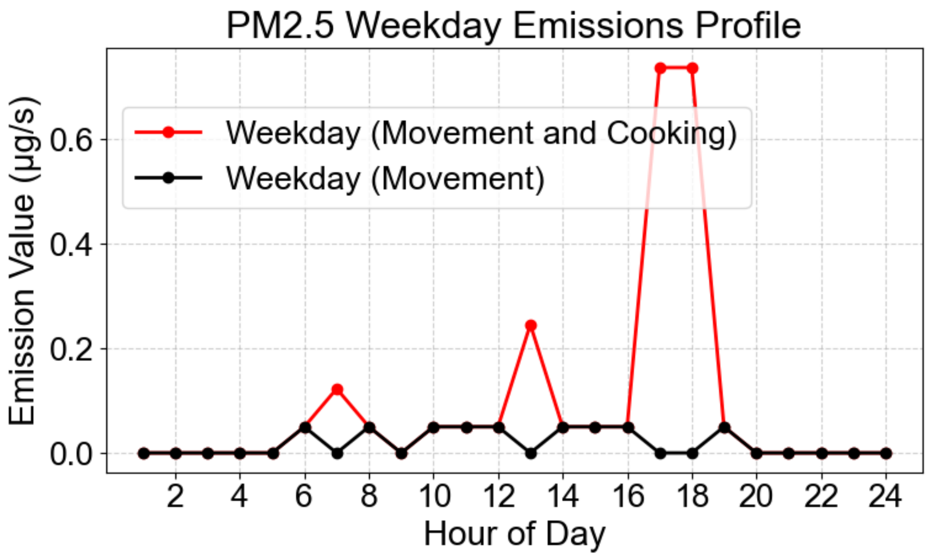
- Processing of data provided:

Dataset	Raw data time interval	Averaging method	Missing data method
Indoor $PM_{2.5}$	Up to 5 minute	Hourly average from up to 5-min intervals	No accounting for missing data
Outdoor air $PM_{2.5}$			Linear interpolation or yearly average diurnal fill
Air exchange rate			Linear interpolation or yearly average diurnal fill

- Usual expression for calculation of emissions:

$$E \text{ (emission)} = A \text{ (activity)} \times EF \text{ (emission factor)}$$

Activity	Assumed variation (differs between weekday & weekend)	Emissions factor reference
Cooking (generic)	Breakfast, lunch, dinner: 5, 10, 30 minutes respectively, times from activity log (allowing for preparation)	Semple et al., 2012
Movement (max.)	Times relating to kitchen activity	Nasir et al., 2013



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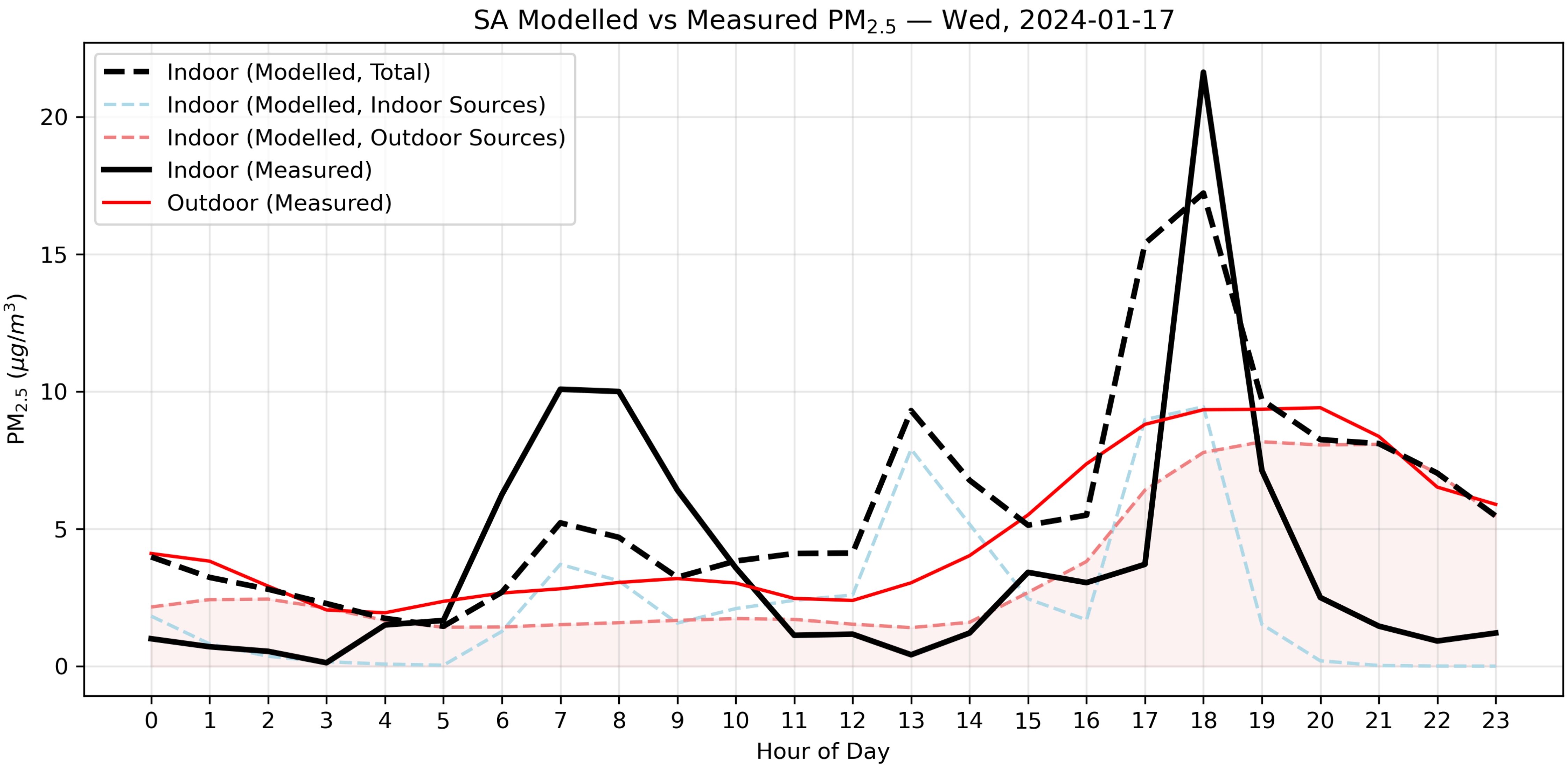
Bradford: typical day, not much ventilation (January)



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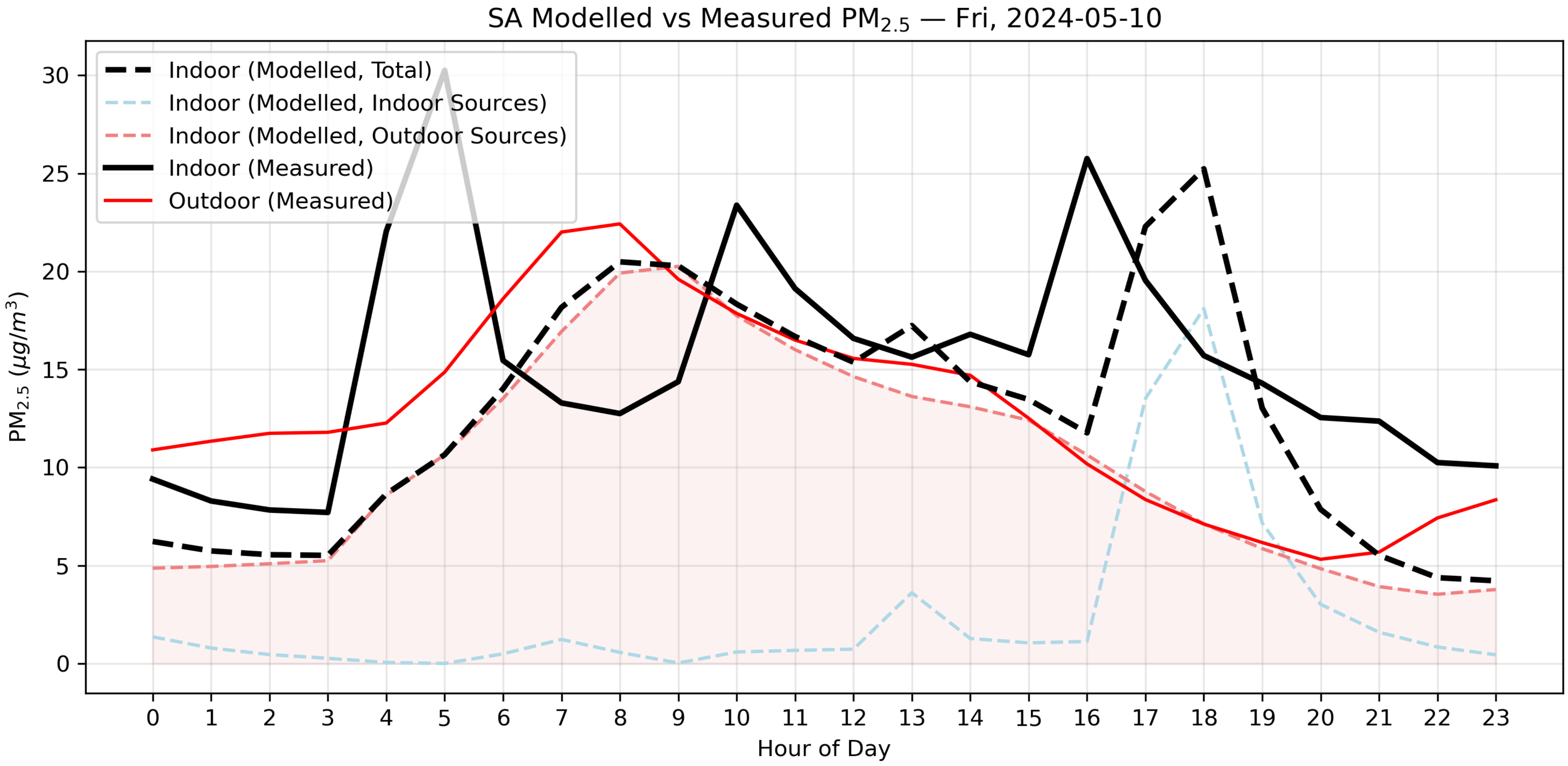
Bradford: typical day, more ventilation (May)



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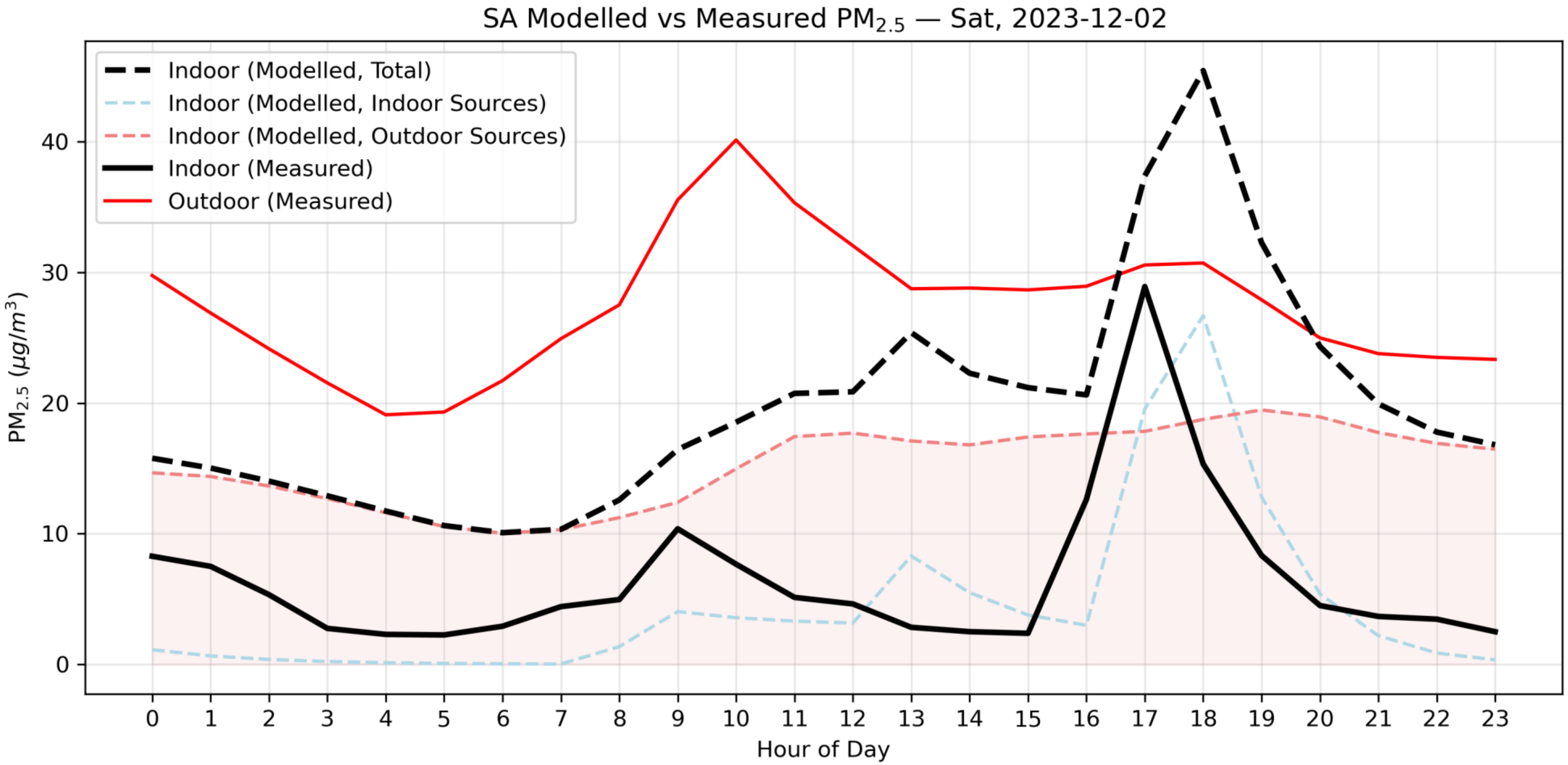
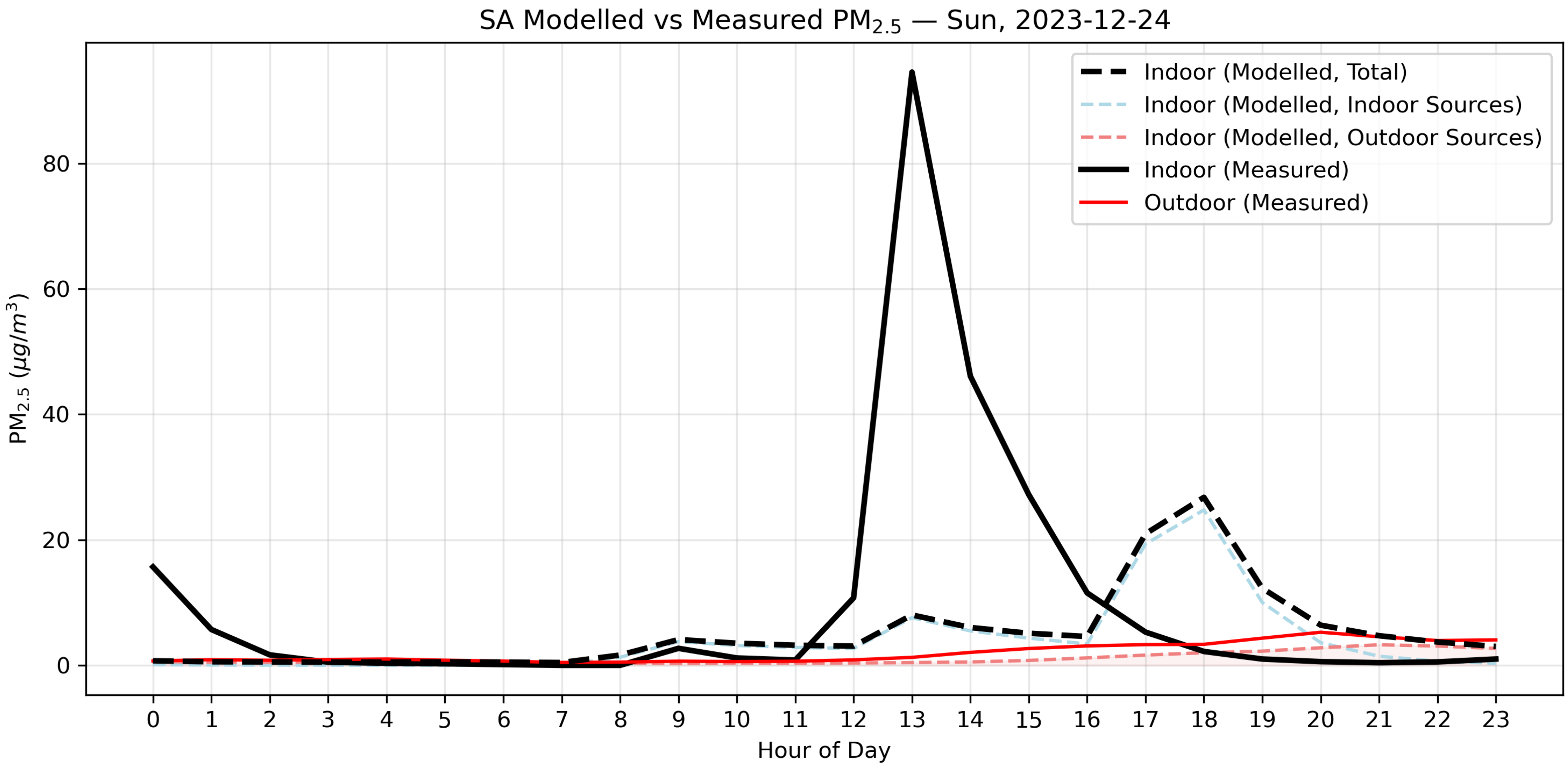
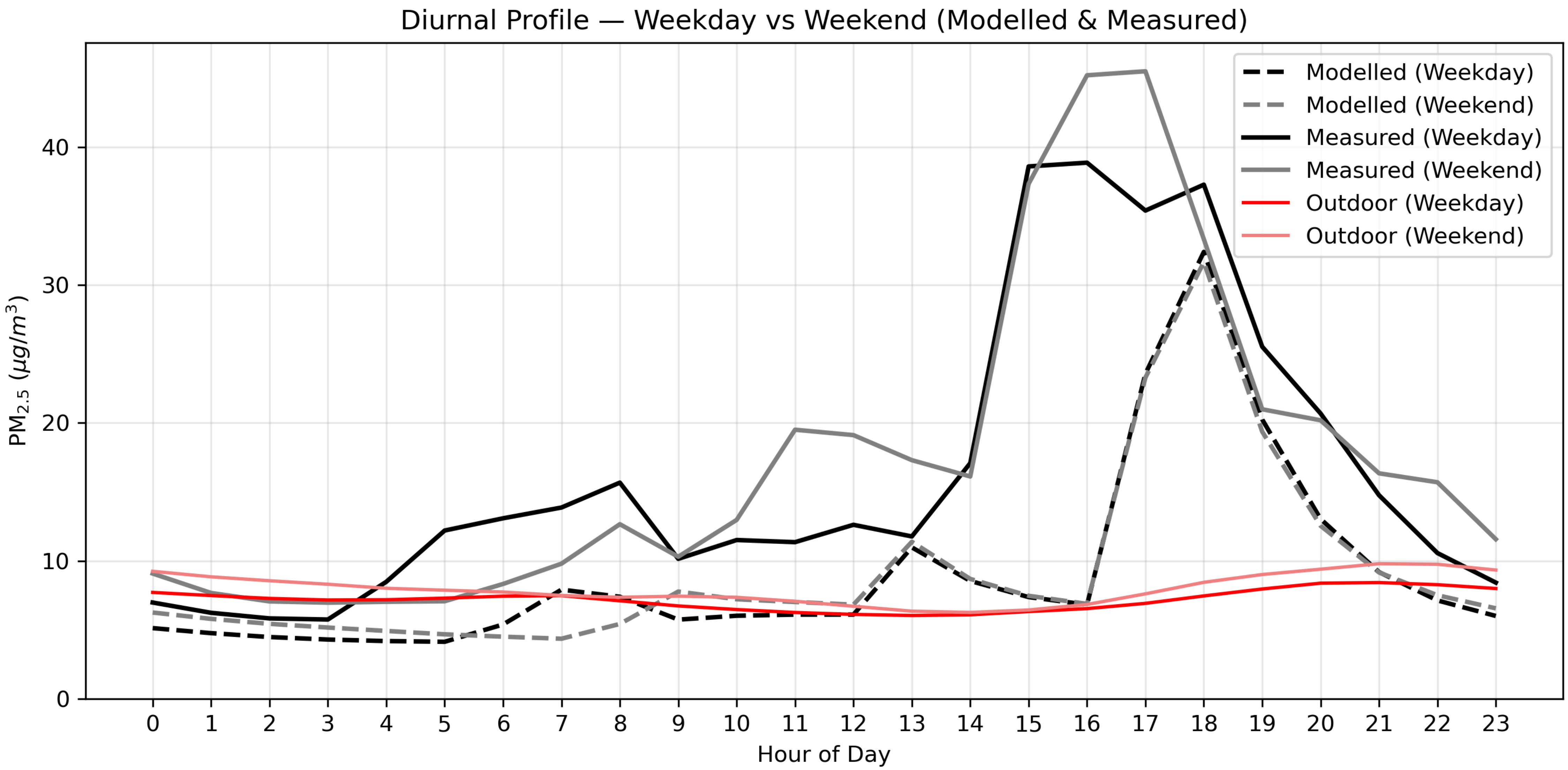
Bradford: no one opened the windows!



Bradford: big lunch on Xmas eve!



Bradford: annual results



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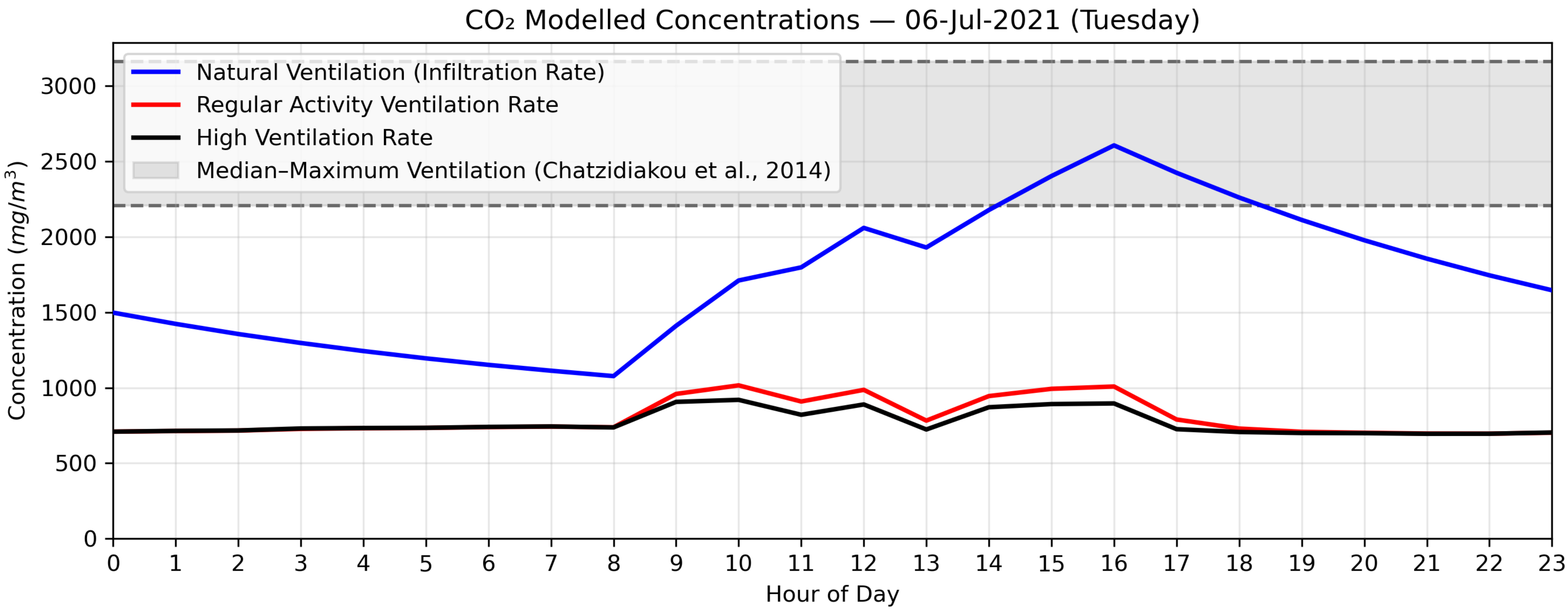
Classroom: setup and assumptions for modelling CO_2

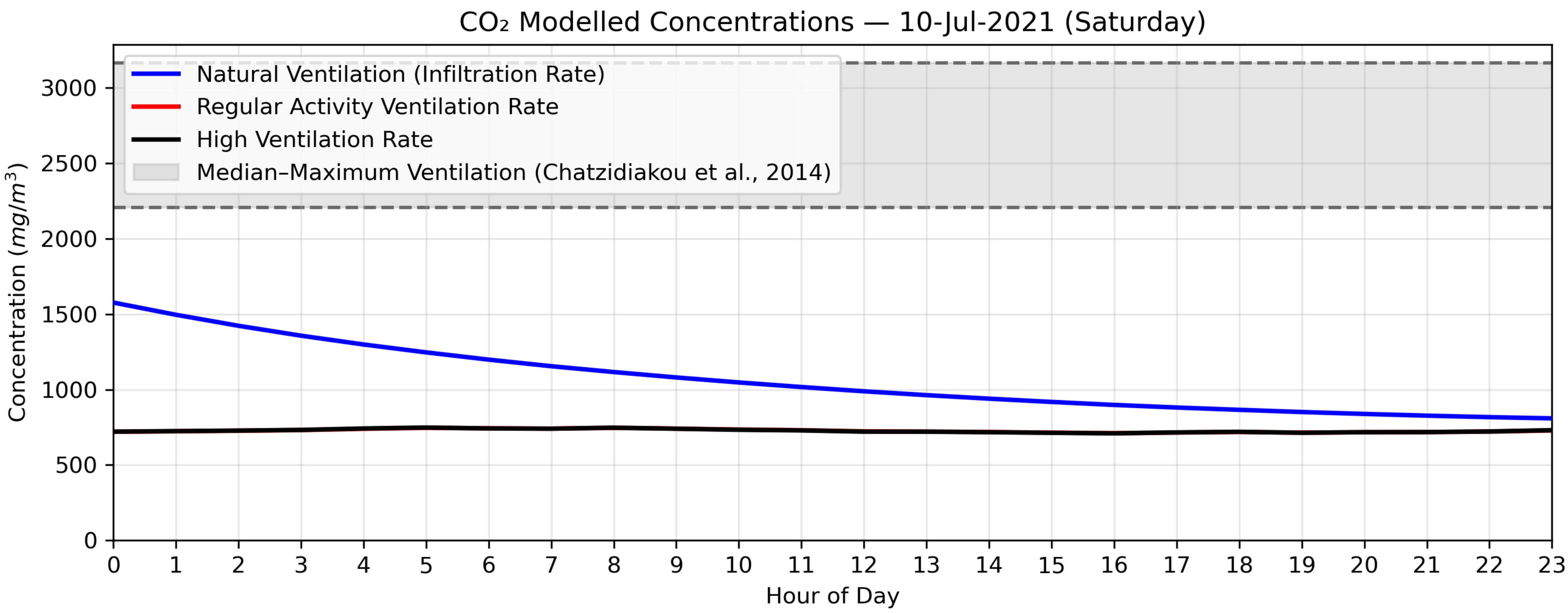
- 28 children in a classroom
- Emissions factors from (Chatzidiakou et al., 2014)
- Classroom volume (Chatzidiakou et al., 2014) (high ceilings ~ 6 m)
- Assumed activity profile:
  - Weekday only
  - School hours
  - Morning and lunchtime breaktimes

- Outdoor CO_2 concentrations from
  - Breathe London project extension funded by NERC, deployed fifteen AQMesh monitors in Glasgow
  - The data from one of these monitors near a school was selected
- Sensitivity testing: 3 ventilation rates (Chatzidiakou et al., 2014) :
  - Low (‘Nature ventilation’)
  - Medium (‘Regular Activity’)
  - High (‘High’)

Classroom: Weekday

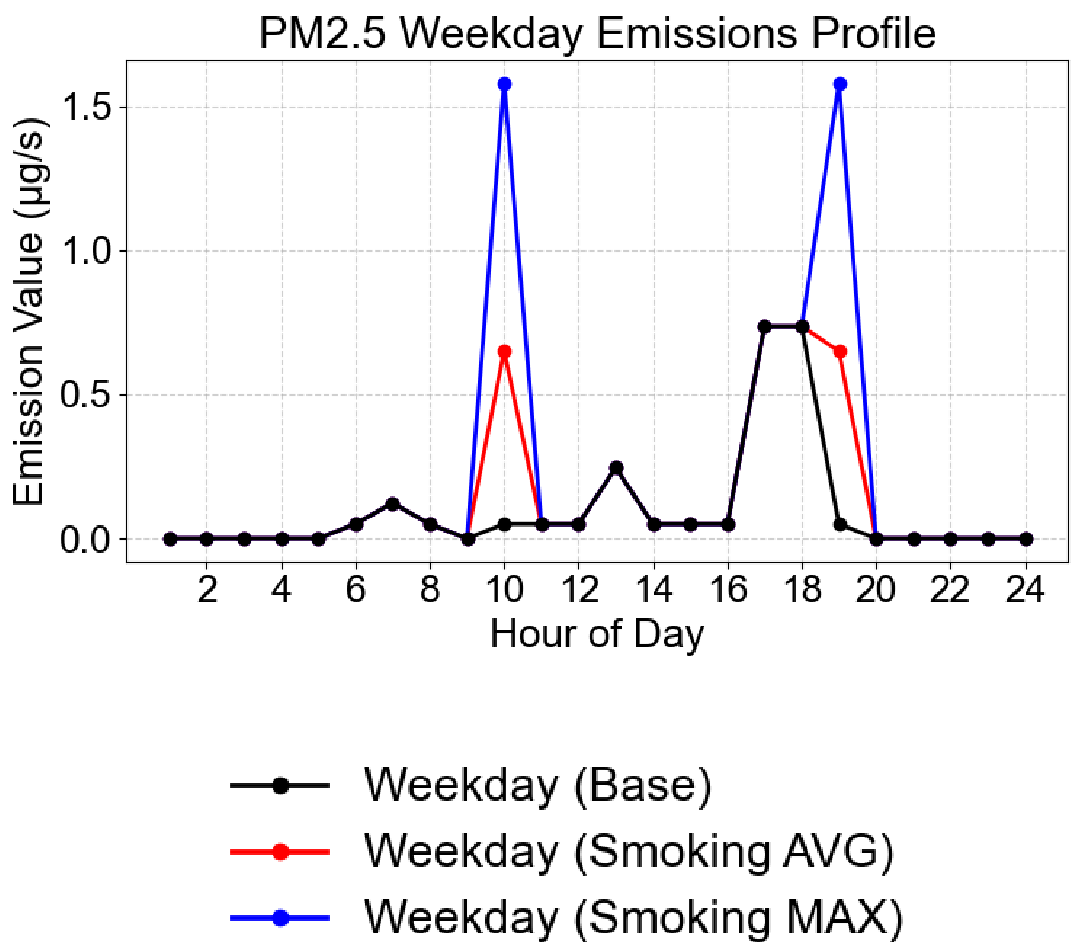


Classroom: Weekend

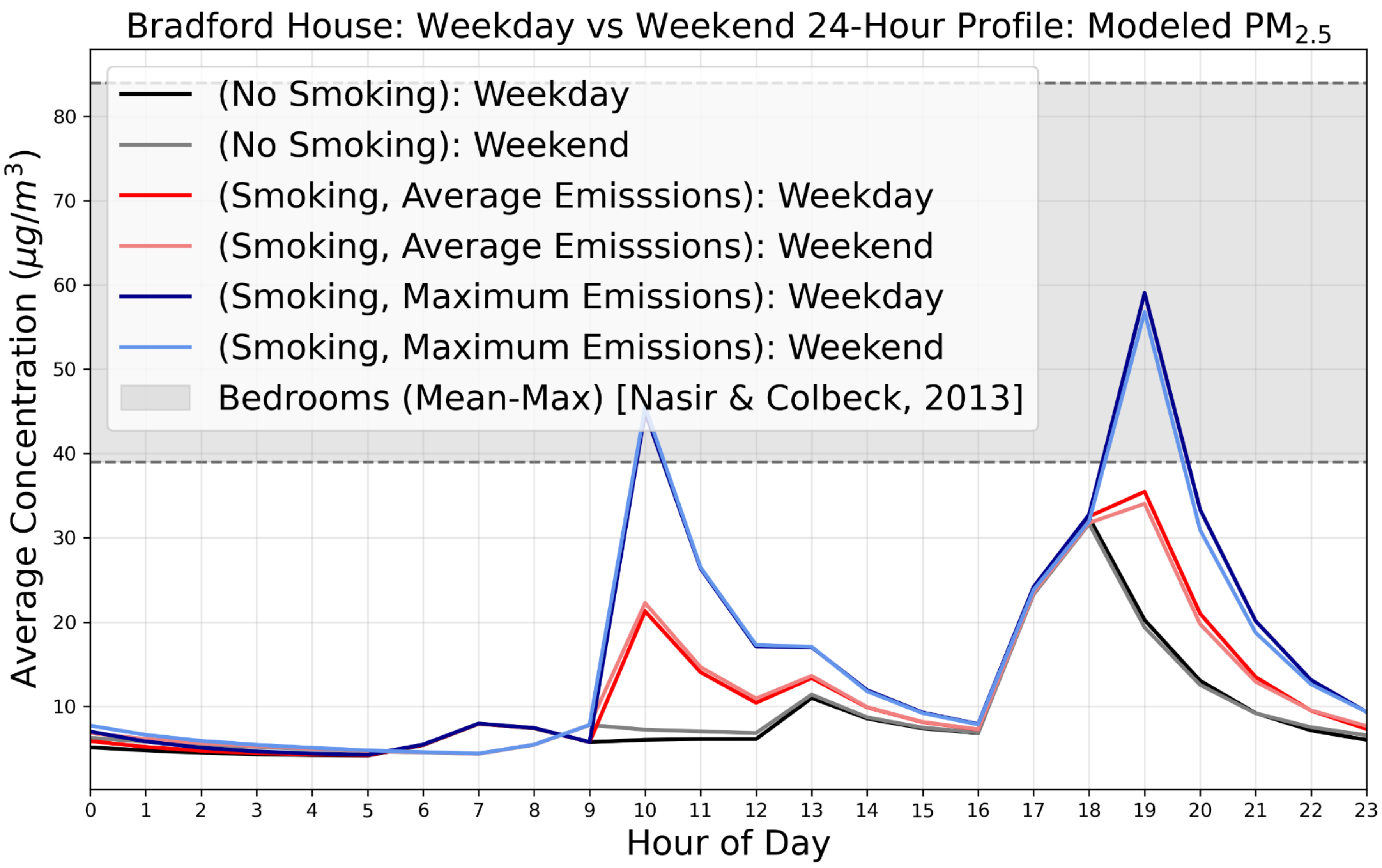


Smoking: hypothetical smoking activity in Bradford house

- Modelling $PM_{2.5}$ based on the Bradford House Data set (smoking residents hypothetical)
- Activity assumed :
  - Max movement + cooking at mealtimes, as before
  - Smoking for 7 minutes during the day (10am, 7pm)
- $PM_{2.5}$ smoking related activity data from Nasir & Colbeck, 2013
- Other model configuration same as for Bradford e.g. ventilation rates & outdoor concentrations



Smoking emissions plus lower levels of movement and cooking at meal times



Conclusions

- A well-mixed model for indoor air quality can predict pollutant concentrations due to both indoor and outdoor sources consistent with measurements
- Hourly comparisons between modelled and measured data for the Bradford case study demonstrate:
  - Detailed ventilation rate information can lead to good estimates of indoor air quality **on average**, even with generic emission rates and approximate activity profiles.
  - **On a day-to-day basis**, differences between modelled and measured indoor concentrations can be larger due to uncertainties in emissions and activity profiles
- Emissions:
  - Some have high uncertainty (e.g. cooking) relating to both the type and time of activity; but others have lower uncertainty (e.g. CO_2 from breathing)

Next steps

- Enhance coupling between indoor air quality model and ADMS
- Further model evaluation
  - Further work with Bradford case study (e.g. measurements from different rooms in the house, if these are made available)
  - Case study for NO_2 relating to combustion (gas boilers, cookers)
    - Relatively few NO_2 indoor air quality measurements due to unreliability of NO_2 sensors. Some campaigns have reference measurement equipment
- Consider if refinements are required, e.g. multiple rooms

Feedback welcome

Thank you for listening

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